

SPATIAL MULTIBODY MODELING AND VEHICLE DYNAMICS ANALYSIS OF A FUTURE TACTICAL TRUCK SYSTEM CONCEPT

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Abstract

The US Army vision, announced in October of 1999, encompasses people, readiness, and transformation. The goal of the Army vision is to transition the entire Army into a force that is strategically responsive and dominant at every point of the spectrum of operations. The transformation component will be accomplished in three ways: the Objective Force, the Legacy (current) Force, and the Interim Force. The objective force is not platform driven, but rather the focus is on achieving capabilities that will operate as a "system of systems." As part of the Objective Force, the US Army plans to begin production of the Future Combat System (FCS) in FY08 and field the first unit by FY10 as currently defined in the FCS solicitation⁽¹⁾. As part of the FCS program, the Future Tactical Truck System (FTTS) encompasses all US Army tactical wheeled vehicles and its initial efforts will focus only on the heavy class. The National Automotive Center (NAC) is using modeling and simulation to demonstrate the feasibility and operational potential of advanced commercial and military technologies with application to new and existing tactical vehicles and to describe potential future vehicle capabilities.

This document presents the results of a computer-based, vehicle dynamics performance assessment of an FTTS concept with such features as a variable height, hydraulic, trailing arm suspension, skid steering, and in-hub electric drive motors. A fully three-dimensional FTTS model was created using a commercially available modeling and simulation methodology and limited validation studies were performed by comparing model predictions with baseline, validated model predictions from another vehicle in the same size and class as the FTTS concept vehicle. The model was considered accurate enough to predict various aspects of ride quality and stability performance, critical to US Army Objective Force mission needs. One-to-one comparisons of the FTTS and a standard, solid-axle, Heavy Tactical Vehicle (HTV) operating in various terrain and obstacle negotiation conditions were performed.

The objective of this paper and presentation will be to describe how M&S is being applied to answer a wide variety of design and performance evaluation questions. It will depict a series of simulation-based engineering projects that

build on the Army's simulation investments as a tool to investigate and answer real-world vehicle design, acquisition, and engineering support questions. Due to much increased HPC computational speeds, memory, and asset availability, entire spectrums of operational mission scenarios are investigated and simulations conducted over a wide range of vehicle speeds and operating conditions. Recent major upgrades in HPC facilities now allow the highly detailed, computationally intensive models to be run in a fraction of the time, and, more importantly, many more 'what if' studies are being performed. Using HPC-based vehicle performance modeling & simulation in support of acquisition allows the Army to evaluate the performance of numerous proposed vehicle system configurations analytically, thereby saving time and costs associated with building and testing actual prototypes. The NAC's M&S efforts using HPC is constantly striving to make the Army a smarter and more cost-effective buyer of equipment, and more importantly, significantly reducing the associated risks that are inherent in procuring newly designed, untested equipment.

INTRODUCTION

The NAC serves as the Army's agent for advancing the development of dual-use automotive technologies by industry, academia and the military services. By cultivating relationships and forming cost-shared partnerships, the NAC accelerates the exchange and implementation of automotive technologies creating developmental savings that are shared by all participants. The U.S. Military requires flexible, effective and efficient multi-mission forces capable of projecting overwhelming military power worldwide. To satisfy this requirement, the joint Army/DARPA FCS program was developed to provide enhancements in land force lethality, protection, mobility, deployability, sustainability, and command and control capabilities. The goal of the FCS program is to design an ensemble that strikes an optimum balance between critical performance factors, including ground platform strategic, operational and tactical mobility; lethality; survivability; and sustainability. This "system of systems" design will be accomplished by using modeling and simulation and experimentation to evaluate competitive concepts as defined in the FCS simulation support plan⁽²⁾. The FCS will be capable of

adjusting to a changing set of missions, ranging from warfighting to peacekeeping, as the deployment unfolds.

What sort of tactical wheeled vehicles will be needed to support the Army in the next decade? To provide accurate answers to that question, the NAC created the FTTS concept (see figure 1) to investigate critical technologies that will be required to achieve stated FCS goals and objectives. Some of the technologies to be explored in this analysis to enhance stability, handling and mobility include; active-variable height hydropneumatic suspensions, advanced hybrid electric propulsion systems, electronic steering, and central tire inflation.



Figure 1. FTTS Concept Vehicle Representation⁽³⁾

FTTS CONCEPT REQUIREMENTS

NAC engineers are using three-dimensional illustrations, models, simulations and various other analyses to help optimize the survivability, mobility and supportability of the Army's future tactical trucks. A combination of virtual prototypes and critical hardware demonstrations will leverage both the Army's technology programs and those from the commercial sector to revolutionize future logistics support. The US Army Objective Force mission requirements will include a heavy tactical vehicle capable of transporting 11 ton payloads on and off road. With armor modules and payload included, this FTTS concept vehicle will have a gross vehicle weight (gvw) which exceeds 25 tons (see figure 2).

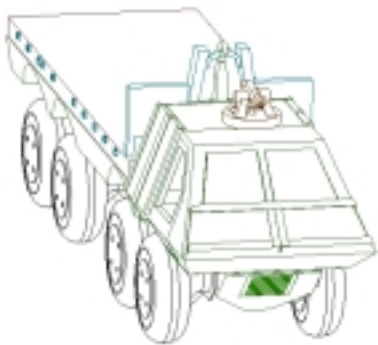


Figure 2. FTTS Concept Vehicle Representation⁽³⁾

It will also feature a palletized load handling system and be capable of transporting 4 and 8 foot ISO containers. The operating requirements for this vehicle are expected to be

much more severe than equivalent vehicles in today's fleet. Due to the lighter overall system weights and increased performance, the FTTS will be required to travel 65 miles per hour (mph) on road and 30 mph off road. The 8x8 FTTS concept has 8 independent, active, in-arm variable height, hydropneumatic trailing arm suspensions which provide approximately 18 inches of wheel travel. It also has 8 in-hub permanent magnet, electric drive motors for vehicle system propulsion that runs silent and can provide braking. The FTTS vehicle maintains an advanced, lightweight, 450 horsepower diesel engine to keep the batteries charged and provide power to the system as required during operation. Lastly, the system has large 16xR20 radial tires with run flat inserts and central tire inflation (CTIS) to maximize off road mobility and payload carrying capacity. The main factors that were analyzed during this analysis to evaluate the stability, handling, ride-quality, and mobility characteristics of the FTTS concept.

APPROACH

NAC engineers used a commercially available vehicle modeling and simulation methodology called DADS⁽⁴⁾, or Dynamic Analysis and Design Systems, to generate and simulate models of the FTTS concept. This model would be suitable for obtaining a better understanding of the vehicle's performance characteristics and for assessing future technology upgrades that could lead to better performance. The FTTS model includes accurate representation of all suspension components to provide adequate predictions of relative displacement between subsystem components. Nonlinear models of suspension stiffness and damping, jounce and rebound stops and steering stops were incorporated to provide accurate interaction force predictions. Individual rotating wheels with nonlinear tire/terrain interaction models that allow the wheels to leave the surface were included in the model to allow large vehicle displacements, including rollover. Rolling tire models that generate fore-aft and side-to-side tractive forces between tire and terrain were included to insure representative mobility predictions. Second order steering and speed control algorithms were used to keep the vehicle model on course and to maintain desired speed based on electronic steering curves and electric motor output curves, respectively.

The FTTS model, loaded to 11 tons, was executed over a number of artificial pothole and bump obstacles defined by NAC engineers. The purpose of these short duration, transient maneuvers was to provide repeatable disturbance inputs to the model with well controlled initial conditions. The model was also executed over a number of straight-line symmetric and non-symmetric variants of the Perryman 2 and 3, and Churchville B courses located at US Army test sites. The simulations were conducted at various speeds to induce different levels of response, and to investigate the upper limits of safe operational performance. A similar

model of the 10-ton heavy tactical vehicle (see figure 3) was developed under a different project.

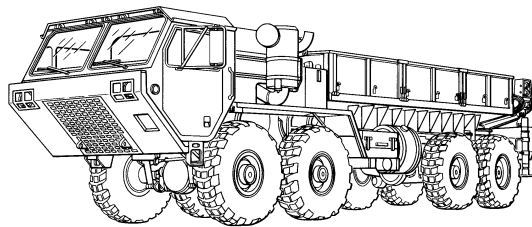


Figure 3. Heavy Tactical Vehicle (HTV)

This model, loaded to 10 tons, was executed over the same obstacles, maneuvers and courses as the FTTS, and at the same speeds so one-to-one comparisons could be made between the two vehicle systems. Side-by-side computer-generated animations of each simulation were made and recorded on video tape for review in real time. Comparison of the results indicated superior FTTS performance over the HTV in all simulations performed. In a number of cases, the HTV showed violent motion or rolled over, while the FTTS showed much less severe motion and remained upright. Based on the above comparisons described in this report, the FTTS appears to be substantially more stable than the HTV, and it should have a higher probability of meeting US Army Objective Force mission requirements.

This paper first describes how a representative FTTS model was defined within the limits of the time and cost budget, and how a representative model was developed. A general overview is first provided of the topology, parameters and performance characteristics of each major subsystem. Then we provide an assessment of how each subsystem might influence the vehicle's operating performance envelope. Details of the 10 ton HTV model are given in (5) and are not presented here. A general overview of the modeling strategy and a description of each major vehicle subsystem model are given to provide a better understanding of the composite vehicle model operation, its interaction with the obstacle and terrain models, and the simulation results. Data and descriptions of each obstacle, maneuver and course profile are presented. The matrix of obstacle negotiations, maneuvers and course negotiations is presented, and simulation results are summarized.

Acquisition of Data for The FTTS Model

Figure 4 shows a computer generated graphical representation of the FTTS model which contains the eight by eight FTTS suspension and 11 ton chassis. The primary purpose of the FTTS is to transport loads up to 11 tons, cross country on rough terrains at moderate speeds, and to maintain mobility, ride quality and dynamic stability while doing so. Most existing commercial and Government vehicles have not been designed for this purpose. The US Army funded the NAC to develop and exploit limited resolution models of the FTTS with high potential new

technologies to assess their influences on mobility, ride quality and dynamic stability properties. The US Army and the NAC believe that the FTTS outfitted with these state-of-the-art technologies has a number of desirable features that will contribute to exceptional performance and decided to exploit and understand the technologies. FTTS vehicle parameters and data was supplied by TARDEC's vehicle concepts group and the rest was calculated or estimated. Representative tire and run-flat data were acquired from the manufacturers. Hydropneumatic springing and damping curves, jounce and rebound stops, as well as roll stiffness and roll center characteristics were all calculated based on payload to weight ratios and mission requirements. Lastly, algorithms were developed to electronically control steering and to control the torques applied to the wheel hubs based on the output curves for the electric motors.

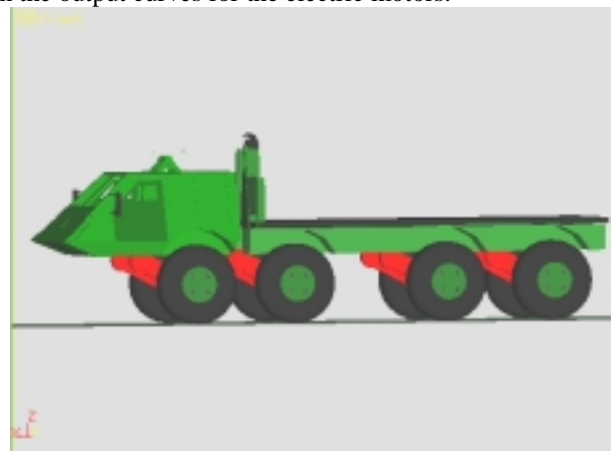


Figure 4. FTTS Graphical Representation

FTTS Body Structure and Model

As shown in figure 5, the chassis contains a rigid ladder frame along the full length of the vehicle that each of the trailing arm units attach to along with the corresponding wheel hub and electric motor assemblies. Each trailing axle pivots up and down to allow the necessary suspension displacement with a jounce and rebound stop installed on each axle to prevent excessive suspension travel. All axles have hydropneumatic arrangements to provide the necessary suspension support and damping. Skid steering is achieved by electronically controlling the electric motors in each wheel to control the wheel speeds to steer the truck. The FTTS steering arrangement allows the wheels to be electronically controlled and is performed by a 2nd order non-linear algorithm.

A brief kinematic description of the model implementation of the FTTS is now presented. The vehicle chassis, including load is represented by a single rigid body. Eight rigid bodies represent the eight trailing axles, and are connected to the chassis body by revolute joints which are aligned with them. Eight additional rigid bodies were used to represent the hydropneumatic springs which are

connected to the chassis by transverse revolt joints at the physical pivot point locations in the vehicle. The remaining bodies are eight wheels connected to the trailing axles and eight wheel hubs connected to the axles. The wheels are connected by transverse revolt joints and the wheel hubs are connected by revolt joints aligned along the wheel axes.

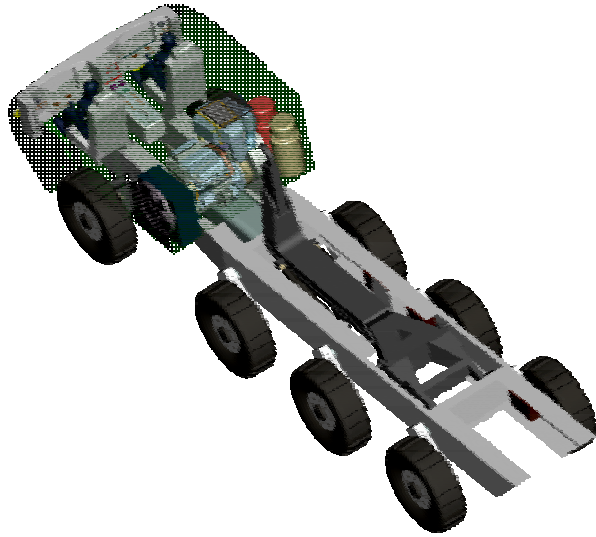


Figure 5. FTTS Graphical Representation⁽³⁾

Suspension, Tire, Powertrain and Steering Models

The vehicle contains a number of hard and soft mechanical stops that must be adequately modeled to insure proper inter-component displacements. A nonlinear translational spring between the chassis and each trailing axle was used to represent the corresponding jounce stops. These springs were placed in line with the physical stops mounted on the chassis, and the hardening rates of the corresponding hydropneumatic springing curves were modeled with nonlinear functions. An additional pair of similar nonlinear springs were placed in line with the rebound stops on the axles. Appropriate metal-to-metal rotational stops to prevent oversteering the wheels was also included. These stops were represented by very stiff nonlinear rotational springs around the attachment revolute joint. In addition, each wheel hub has a rotational stop to limit maximum rotation relative to the axle. These hard stops are represented by stiff nonlinear rotational springs around the corresponding wheel axes. Compliance in the hydropneumatic suspension was represented by connecting vertical translational springs between the chassis and the center of the corresponding trailing axle bodies. The translational spring rates were set equal to the effective hydropneumatic stiffnesses in loading and unloading. Damping was also included in each suspension unit.

The tires were modeled by nonlinear springs that allow the interaction forces to go to zero when they leave the

ground. The vertical force developed between the FTTS tires and a non-deforming ground surface as a function of vertical tire deflection was taken from tests performed on this tire. Additional data causing the curve to increase nonlinearly to emulate hardening effects due to bottoming out on the rims was added. Also the output force is zero for all negative displacements. The vertical stiffness rate corresponds to a cross-country tire inflation rate. The tire model also computes the relative slip velocity between the bottom of the tire and ground. This slip velocity is used to compute a fore-aft slip between zero and 100 percent which is inserted into the longitudinal friction curve. The coefficient of friction from this curve is then multiplied by the normal force to obtain the longitudinal frictional force. This force always acts on the tire in the opposite direction of the relative slip. A lateral slip angle in radians is also computed from the two components of forward and lateral slip velocity and inserted into the curve. To find lateral tire forces for vertical forces, the curves are interpolated with vertical tire force and slip angle values to obtain lateral force magnitudes and directions. These forces are applied to the wheel bodies to support the vehicle and control it. All tire data used here is given in. The wheels are driven by a speed control algorithm. A desired constant or variable speed control signal based on the in-hub electric motors as input to the model is used as a reference. The speed of the vehicle is determined by projecting its velocity vector along the chassis fore-aft centerline. This result is compared to the desired speed and a corrective torque is generated. This torque is applied to each wheel to propel or brake the corresponding wheel, which effectively controls the vehicle motion. A simple steering algorithm monitors the vehicle's centerline alignment with, and its deviation away from a designated trajectory. These two error signals are converted into a steering torque that is applied at each wheel to steer the vehicle. The gain in this controller model was made inversely proportional to vehicle speed to reduce steering sensitivity at higher speeds for better steering stability.

TEST SCENARIOS

The FTTS model, loaded to 11 tons, and the HTV model loaded to 10 tons were executed over a number of defined artificial pothole and bump obstacles. Each obstacle was set up so only the left side tires encountered it in order to induce significant nonsymmetrical transient responses. A number of lane change and slalom maneuver simulations were also conducted. The purpose of these short duration, transient maneuvers was to provide repeatable disturbance inputs to the model with well controlled initial conditions. The model was also executed over a number of straight-line symmetric and nonsymmetric variants of the Perryman 2 and 3, and Churchville B courses. The simulations were conducted at various speeds to induce different levels of response, and to investigate the upper limits of safe operational performance. The following computer-based

simulations were set up primarily to determine trends and investigate upper stability limits of the vehicle systems:

Cross Country Courses

Vehicle models were set up to negotiate 180 foot sections of straight-line representations of portions of measured left and right track elevation profiles of Churchville B, Perryman 2, and Perryman 3 course as functions of distance traveled along the course were used. The two tracks are assumed to be 6 feet apart corresponding to the approximate track width of the vehicles. Each of these courses was also modified by shifting the left track 9 feet ahead of the right track to simulate non-symmetrical terrain inputs to the vehicles. Results obtained from the vehicle simulations on these course segments should not be taken as indications of how the corresponding vehicles would perform on the actual courses because these courses also contain hills, curves and soil properties not included in the models. The results should be used primarily for making comparisons between the two vehicles as they would perform on these artificial course segments.

Lane Change Maneuvers

This set of simulations emulates a double lane change/obstacle avoidance maneuver. This set of simulations emulates an obstacle avoidance or slalom maneuver. Each maneuver executes a lateral transition to the left and a reverse transition back to the original lane.

Single Bump Negotiation

This set of simulations emulates the negotiation of artificially constructed ramps and potholes. The simulations were performed on various ramp heights and pothole depths and only the left side wheels of the truck encounter the disturbances.

VARIABLES RECORDED AND SIMULATIONS CONDUCTED

In order to determine the FTTS's stability characteristics, we included several cross country courses in the test matrix. These cross country courses vary in roughness and also in the amount of roll they induce. In addition to these cross country courses, the test matrix included lane change and slalom maneuvers. These maneuvers are instrumental in determining a vehicle's Lateral Acceleration Threshold (LAT). The LAT is the highest lateral acceleration a vehicle can withstand without rolling over. Because we were performing comparisons between vehicles, rather than tabulating a list of lateral accelerations, we ran the lane change simulations at speeds high enough to cause one vehicle to roll over. In both cases, the HTV rolled over at 64 km/h and the FTTS remained upright. The test matrix also included several pothole and bump obstacle courses. These courses excite the vehicle system with a single discrete event which enables us to

easily compare the effects of suspension jounce clearance by measuring the percent of time on jounce stops. Though not as pronounced as the cross country courses, the courses do impart significant roll and pitch motion to the vehicle system, thereby allowing us to compare vehicle roll and pitch compliance. Table 1 gives a summary of the different simulations performed.

File names	Course Description (m=meter)	Speeds (km/h)
chvb16,32,48	Churchville B - 152 m	16, 32,48
prm216,32,48	Perryman 2 - 152 m	16, 32,48
prm2os16,32,48	Perryman 2-152 m	16, 32,48
prm316,32	Perryman 3-152 m	16,32
prm3os16,32,48	Perryman 3-152 m	16,32,48
lane32,48,64	lane change-3.3x27.4 m	32,48,64
.2286ph32,25	pothole-.2286 m deep	32,25
3048ph16,32,40,48	pothole-.3048 m deep	16,32,40,48
.4572bp24,32	bump-.4572 m high	24,32
.6096bp16	bump-.6096 m high	16

Table 1. Simulations Performed on Vehicles

The FTTS and HTV simulations are most suitable for analyzing ride quality, and to a lesser extent for quantifying vehicle stability. To help obtain qualitative assessments of ride quality in the two vehicles, a number of accelerations, and force and torque time histories of both vehicle systems were plotted. Because the two vehicles have different suspension designs, one cannot always make one-to-one comparisons between amplitudes of corresponding variables. In some cases, it may be necessary to compare relative magnitudes within the particular plots. For example, in the FTTS an axle's angle is a direct indication of the corresponding suspension displacement, whereas, in the HTV an axle's spring displacement indicates the corresponding suspension displacement.

RESULTS AND DISCUSSION

Due to limited space requirements, results will be summarized in the following sections and in the conclusions. Plots of selected FTTS and HTV state variables for the simulations performed on the 152 meter cross country course segments, lane changes, pothole and bump negotiations, and power spectral density computations on the vertical component of chassis translational acceleration, and the pitch and roll components of chassis rotational acceleration at the vehicle speeds indicated in Table 1 will be discussed. When performing a computer-based vehicle analysis, we generally compare the vehicle's response with a 'similar' vehicle. We simulated the HTV executing the same test matrix as used for the FTTS. Evaluating the FTTS becomes a matter of comparing state variables that lend insight to vehicle stability and ride quality characteristics.

Stability Analysis - Roll Stability Comparisons

A major stability concern is vehicle roll compliance. Roll compliance is the ability of a vehicle suspension to absorb terrain roll undulations without imparting them to the sprung mass. To quantify the roll compliance, we recorded the chassis roll angle and the roll acceleration for each vehicle and processed these data to determine the maxima, minima and root mean square (RMS) values. When a vehicle rolls over or the motion becomes extremely violent, the accelerations and angles can become so large that they dwarf the other data samples. This makes it difficult to compare the other good data. To avoid this problem, we replaced the exceptionally large positive values by small 'negative' values in the bar charts so they could be readily identified as representing ignored data points. A bar chart comparing both vehicles while traversing the cross country courses is shown in Figure 6. With the exception of the HTV rollovers and the near-rollover on Churchville B at 48 km/h, the RMS roll angles of both vehicles are comparable with the FTTS values averaging slightly less. In a similar manner, the vehicle roll accelerations are comparable with the FTTS roll accelerations being significantly less.

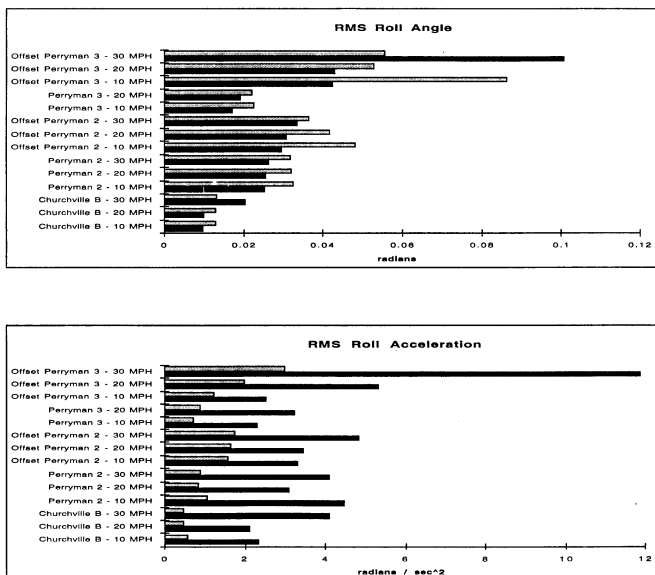


Figure 6. HTV-light color bar, FTTS-dark color bar

Stability Analysis - Pitch Stability Comparisons

Pitch compliance is an indicator of a suspension's ability to absorb terrain pitch undulations without imparting them to the sprung mass. To quantify pitch compliance we recorded the chassis pitch angle and pitch acceleration for each vehicle and processed these data to determine the maxima, minima and RMS values for both vehicles on the cross country courses. Again, small negative entries identify HTV rollover or near-rollover events. A bar chart comparing both vehicles while traversing the cross country courses is shown in Figure 7. With the exception of the

HTV rollover and near-rollover cases, the RMS pitch angles are comparable with the HTV angles being generally higher. Except for HTV rollover and near-rollover cases, the RMS pitch accelerations are comparable. However, when the pitch accelerations are small, the HTV does better, but the FTTS does better when the pitch accelerations are large.

Stability Analysis - Percent Time Tire Airborne

For the driver to maximize vehicle stability, the foremost rule is to keep the tires on the ground as much as possible. To determine the ability of each vehicle to do this, we computed the percent of time each tire was off the ground. To facilitate comparison between vehicles, we averaged these percentages for each simulation to produce a percentage airborne-time. As above, small negative bar chart entries denote HTV rollover or near-rollover events. In general, the FTTS performed much better than the HTV in this situation. A bar chart comparing both vehicles while traversing the cross country courses is shown in Figure 8.

Ride Quality

Vertical Acceleration at Chassis Center of Mass - An important factor when considering a vehicle's performance is its ride quality. The ride quality is a measure of the severity of the ride and reflects the likelihood of passenger injury, component failure and payload damage. In order to compare ride quality characteristics, the vertical acceleration of the chassis center of mass was recorded. Small negative bar chart entries denote HTV rollover or near-rollover events. At the lower speeds, the vertical accelerations were comparable. At the higher speeds, the FTTS performed considerably better than the HTV. A bar chart comparing both vehicles while traversing the cross country courses is shown in Figure 9.

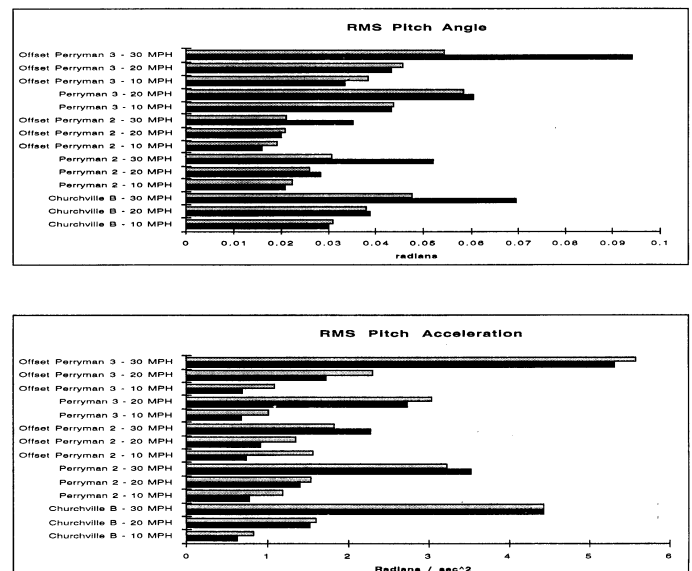


Figure 7. HTV-light color bar, FTTS-dark color bar

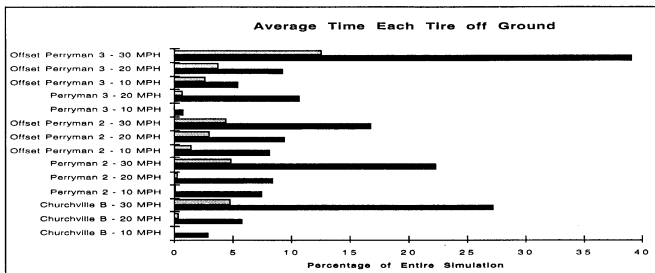


Figure 8. HTV-light color bar, FTTS-dark color bar

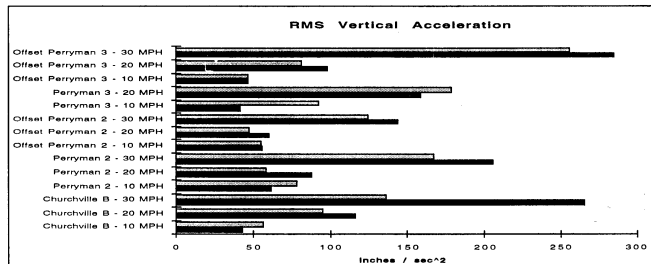


Figure 9. HTV-light color bar, FTTS-dark color bar

Percent Time in Jounce Contact

Because of the larger forces imparted by severe jounce impacts, the likelihood of component failure increases with the number events. Therefore we computed the percentage of time each jounce stop was in contact. To facilitate comparison between vehicles, we averaged these percentages for each simulation to produce a percentage jounce contact time. Small negative bar chart entries denote HTV rollover or near-rollover events. The FTTS performed much better than the HTV in all situations. A bar chart comparing both vehicles while traversing the cross country courses is shown in Figure 10.

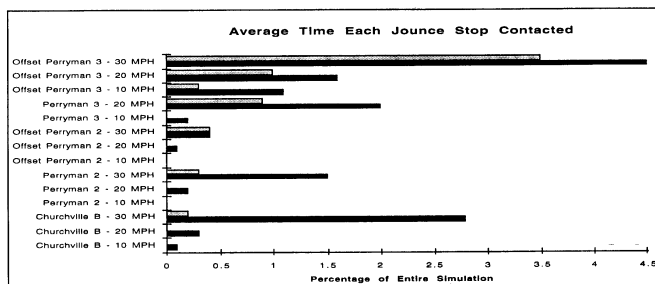


Figure 10. HTV-light color bar, FTTS-dark color bar

Power Spectral Density (PSD)

Although the systematic counting and timing techniques outlined above are useful for determining vehicle stability and ride quality characteristics, the possibility exists that a given terrain profile at a given vehicle speed, may have a dominant spatial frequency that excites the vehicle and its suspension at some natural frequency. This could cause a

vehicle/road interface resonance condition that may result in violent motion with subsequent loss of control. This resonance phenomena could also induce significant chassis and component flexure, and result in premature component failure. In general, a driver would instinctively avoid these resonance conditions by speeding up or slowing down, to move the profile's spatial frequency input to some other value that does not match the vehicle's natural frequencies. However, the driver model employed in these simulations was programmed to maintain a constant speed.

To investigate the possibility that either vehicle may have been operated near a resonant condition which would bias the results, we checked for possible terrain-induced resonances and the speeds that would cause them. To determine where vehicle/road resonances occur, we first computed PSD's of the terrain elevation profiles corresponding to a vehicle speed of 1.6 km/h. We compared these frequencies with the natural frequencies of the vehicles for all cross country courses. The peaks in the PSD plots indicate the dominant frequencies for the courses at 1.6 km/h as shown in Table 2.

Churchville B - 1.6 kph

	Freq1	Mag1	Freq2	Mag2	Freq3	Mag3
Left	.016	3980	.028	794	.050	316
Right	.016	3980	.028	794	.050	316
Roll	.016	.004				
Pitch	.016	0.32				

Perryman 2 - 1.6 kph

	Freq1	Mag1	Freq2	Mag2	Freq3	Mag3
Left	.016	794	.018	630	.022	316
Right	.016	794	.018	630	.022	316
Roll	.016	.016	.026	.006		
Pitch	.016	.050	.024	.050		

Offset Perryman 2 - 1.6 kph

	Freq1	Mag1	Freq2	Mag2	Freq3	Mag3
Left	.016	794	.018	630	.022	316
Right	.016	794	.018	630	.022	316
Roll	.016	.158	.023	.158		
Pitch	.018	.040	.016	.035		

Perryman 3 - 1.6 kph

	Freq1	Mag1	Freq2	Mag2	Freq3	Mag3
Left	.035	2512	.018	2399	.025	1514
Right	.035	2512	.018	2399	.025	1514
Roll	.020	.006	.022	.006	.063	.002
Pitch	.035	.251	.030	.200		

Offset Perryman 3 - 1.6 kph

	Freq1	Mag1	Freq2	Mag2	Freq3	Mag3
Left	.035	2512	.018	2399	.025	1514
Right	.035	2512	.018	2399	.025	1514
Roll	.032	.631	.018	.501		
Pitch	.035	.158	.032	.063		

Table 2. Dominant Freq. of Cross Country Courses

To determine the natural frequencies of the vehicle systems, PSD's of chassis vertical, roll and pitch accelerations were computed and analyzed for all of the simulations. The bump and pothole obstacle course simulations are ideal for determining a vehicle's natural frequencies because each imparts a single short duration impulse. Because small amount of energy in this discrete event, most of the spectral information is derived from the vehicle settling response. Consequently, the peaks in these PSD's will indicate the vehicles' dominant natural frequencies, depicted in Table 3.

	Vert Acc Freq (Hz)	Roll Acc Freq (Hz)	Pitch Acc Freq (Hz)
MTVR	1.1	1.0	1.1
FTTS	1.8	2.4	1.5

Table 3. Vehicle Dominant Natural Frequencies

As noted earlier, the HTV's smaller suspension clearance resulted in considerable jounce stop contacts. Nonlinearities caused by these impacts generated a broad spectrum of frequencies, and made it more difficult to pinpoint the natural frequency of the HTV. Therefore we looked for possible resonances by searching for anomalous maxima in the cross country PSD's. After analyzing the PSD's and the jounce stop impact data, we believe the vehicle rollovers in the simulations were caused primarily by jounce stop impacts rather than vehicle/road resonances.

CONCLUSIONS

The most obvious result of this analysis was that the FTTS completed the entire test matrix without rolling over, whereas the HTV rolled over on several cross-country courses and lane change maneuvers. Assessments of the animations and data indicate that the FTTS has superior performance over the HTV in the US Army mission environments. One factor which may have contributed to improved FTTS performance is that the HTV payload may be a proportionally higher than the load on the FTTS. These may have combined to give the FTTS a lower center of

mass, and the increased inertia gave it lower roll, pitch and jounce natural frequencies than the HTV. These, plus the optimized damping ratios, may have combined to improve overall system performance. Another factor which may have contributed to improved FTTS performance is that the FTTS has a larger pitch radius of gyration, while the effective support distances between the front and rear of both vehicles is about the same (approximately 180 inches). The HTV pitch radius of gyration is close to 90 inches, while the FTTS pitch radius of gyration is somewhat less. The lower pitch radius of gyration, combined with the lower natural frequencies may result in better dynamic performance. These simulations showed that both vehicles performed well in the harsh operating environments. Any vehicle designed similar to the FTTS and operating in a similar payload range should exhibit excellent dynamic performance characteristics for the types of off-road operations expected in the field.

REFERENCES

1. Defense Advanced Research Projects Agency/Army Future Combat Systems Program Solicitation, Solicitation No. PS 02-07, Program Manager, Objective Force.
2. Simulation Support Plan, Future Combat Systems (FCS), Future Combat Systems Program Office.
3. Halle, Nance Lee, and Feury, Mark, "Future Tactical Truck Systems" presentation, 18 September, 2001.
4. Dynamic Analysis and Design Systems, Computer Aided Design Software, Inc., PO Box 203, Qakdale, Iowa 52319.
5. Letherwood, Michael, and Gunter, David, "Computer-Based Dynamic Analysis and Assessment of Heavy Tactical Vehicle Concept Configurations", Tank-Automotive Research, Development, and Engineering Center Report#12689, August 1997.